EARTH SATELLITE CORPORATION E83-10325

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SECOND QUARTERLY PROGRESS REPORT UNDER CONTRACT NAS5-27384

STUDY OF LANDSAT-D THEMATIC MAPPER PERFORMANCE AS APPLIED TO HYDROCARBON EXPLORATION

Period Covered: January 7, 1983 to April 7, 1983

I. During this reporting period, EarthSat was able to perform a first substantial analysis of Thematic Mapper data, and to make a first evaluation of its potential use for hydrocarbon exploration. The results of this work, together with analytical work concerning band image selection for Thematic Mapper data, are contained in three reports: (1) "Evaluation of Thematic Mapper Performance as Applied to Hydrocarbon Exploration," (2) "Implications of Information from Landsat-4 for Private Industry," and (3) "Selecting Band Combinations with Thematic Mapper Data" (attached). The following summary comments are in large part taken from the above reports. Presentation of these results was made at the Landsat Early Results Symposium (February 22-24, 1983) and the Goddard Memorial Symposium (March 24-25, 1983).

II. A. Analysis of a July 25, 1982 scene of southern Ontario shows that TM data permits improved delineation of known oil and gas fields. Visible lineaments appear to be the surface expression of major through-going structures, controlled by subsurface fracturing, not readily visible on earlier MSS data.

B. The use of hue, saturation, and value (HSV) image processing techniques on the Death Valley scene of 17 November 1982 permits direct comparison of TM processed imagery with existing 1:250,000 scale geological maps of the area. In particular, small outcrops of Tertiary volcanic material overlying Paleozoic sections show a detail not provided by the geologic maps. This type of comparative mapping is not possible using natural color or standard false color presentations of TM data. In fact, the processing employed all 7 TM bands, with a TM 5/TM 2 ratio controlling hue, a TM 5/TM 7 ratio controlling saturation, and the first principal component combination controlling the value.

TM 2 was chosen for its sensitivity to iron oxides, TM 7 (2.2 microns) for its sensitivity to hydroxyl bands, and TM 5 for its high variance.

C. Analysis has just begun of TM data over Lawton, Oklahoma. We believe that we see evidence that the reducing chemical environment associated with hydrocarbon microseepage has changed ferric iron

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to soluble ferrous iron, allowing it to be leached from the Rush Springs Sandstone, with a consequent bleaching of the surface. To date, this work has been done using only interactive computer displays, and the next stage of analysis will be the production of enhanced hard copy outputs.

D. The Owl Creek, Wyoming scene has been received, but the light dusting of snow that covers much of the area will, we believe, hinder spectral analysis of this imagery. However, the alteration on this scene associated with the Copper Mountain uranium deposit is visible. The overall configuration of the Owl Creeks suggest that they lie within a major left-lateral wrench zone broken by northwest trending thrust faults paralleling the Wind River thrust to the southwest. We regard the amount of structural information available in this scene as spectacularly high.

E. The band selection algorithm referenced above has been applied to each scene and each subscene analyzed. The results show a surprising consistency, with the 1,4,5 combination selected as optimal in almost all cases. This has been true in scenes as diverse as Washington, D.C., Death Valley, and Lawton, Oklahoma. The same computation shows that both the natural color (1,2,3) and the standard false color (2,3,4) combinations lie far down in the rankings. The production of 1,4,5 hard copy images confirms that this combination usually provides more and more easily interpretable information than either the natural or standard false color images, at least so far as geological analysis is concerned.

III. General Comments and Problem Areas

Discussions at the February Early Results Symposium make it clear that many investigators are exploring the radiometric and geometric properties of TM imagery and evaluating the performance of the sensor system, but no other group is evaluating the instrument's performance in the context of hydrocarbon exploration. We therefore think it logical that we should emphasize the latter aspect, while working closely with other investigators to minimize duplication in engineering evaluation of the system.

In this context, two main factors are presently limiting our activities. First, we have found it difficult to obtain cloud-free, snow-free imagery over the test site areas of interest for hydrocarbon exploration. Second, our analysis to date has been limited to P tapes. Since a number of our evaluation activities depend upon radiometric modification of line data, access to A tapes is important.

Continued analysis of test site data for structural features, evidence of hydrocarbon microseepage, and botanical anomalies, together with processing of A tape data, will constitute major activities of the next quarterly period.

EVALUATION OF THEMATIC MAPPER PERFORMANCE AS APPLIED TO HYDROCARBON EXPLORATION

Dr. John R. Everett, Dr. Charles Sheffield, Dr. Jon Dykstra
Earth Satellite Corp., 7222 47th Street, Chevy Chase, MD 20815

Results from a limited sample of Landsat-4 TM scenes demonstrate that the greater number of spectral bands and the increased spectral and spatial resolution over previous satellite data greatly expand, improve and refine the geological inferences possible from space. The number and narrower width of available spectral bands, coupled with digital processing techniques such as band ratioing, principal component analysis and hue-saturation-intensity presentation, allow the differentiation and mapping of a large number of geologic units and the identification of altered rock associated with intrusions in the Death Valley, California area. These capabilities will contribute greatly to geologic exploration in arid areas.

The increased spatial resolution also assists in distinguishing glacial from tectonic features (difficult on previous imagery) in the Detroit area. Several of the Ordovician oil and gas fields of Ontario lie on fracture zones clearly visible on Landsat-4 imagery. All of these fields rely on fracture-related porosity and permeability for production. The current-borne sediment plumes in Lake St. Clair and Erie demonstrate that Landsat-4 will contribute to our understanding of lacustrine, riverine and marine depositional and erosional patterns and processes.

Digitally enhanced Landsat-4 TM imagery reveals geological features of the Anadarko Basin, Oklahoma, in greater numbers and detail than previously possible. Comparison with existing work suggests that some of the subtle spectral differences detected are related either to changes in chemical composition or resultant changes in vegetation related to micro-seepage of hydrocarbons adjacent to oil fields in the area.

There seem to be several categories of features (throughgoing structures, large area subtle tonal contrasts, etc.) that are still best seen on older

Landsat imagery. Thus, Landsat-4 does not make earlier systems obsolete; rather, it provides a powerful new tool to exploration geologists.

There is a fortuitous synchronous development of satellite remote sensing, and the concepts of plate tectonics and vertical migration of hydrocarbons - two paradigms which are reshaping geological exploration thinking. The steadily improving quality of satellite data is providing geologists with a valuable tool with which to test, revise and exploit these new concepts.

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TM AND GEOLOGIC EXPLORATION

Since the early 1960's, the science of geology has been undergoing a major revolution. The new paradigm of plate tectonics and seafloor spreading is replacing the older paradigm of a rigid, stable earth. Inherent in the acceptance of plate tectonic theory is a growing appreciation of the role of plate motion in determining the location of mineral deposits and hydrocarbon accumulations. It is fortunate that developments in spaceborne remote sensing have paralleled these developments in geologic thinking. As a consequence, we have remote sensing tools that view the earth with appropriate scale and scope to enable us to appreciate and map the regional structures that reflect the motions of continent-sized segments of the earth's crust. We received our first glimpses of the earth from space with photos from the Apollo and Gemini flights. The first three Landsat satellites gave us near ubiquitous high resolution (80 metre) coverage in four spectral bands. These data have had and continue to have enormous impact on all facets of the perception and management of renewable and non-renewable natural resources and the environment.

Before speculating on the impact of the new data types from Landsat-4, it is useful to take a look at the role data from the first three Landsat satellites have in geologic exploration and their current level of acceptance. In a general sense, Landsat data has made its major contribution to hydrocarbon exploration in the spatial domain. In mineral exploration, Landsat has revealed some spectral information, but again the major contribution is spatial. The synoptic view of over 34,000 square kilometres of the earth's surface on a single Landsat image permits the detection and mapping of major regional structures associated with the geologic development of entire geologic provinces. It is also possible, through special digital enhancements, to map some of the more subtle surface expressions of fracturing, folding and alteration associated with buried hydrocarbon accumulations and the emplacement of mineral deposits. The data make it possible to interrelate widely separated geologic features and detect subtle changes that occur over tens of miles and, hence, have gone unnoticed on conventional types of data. Perhaps most important of all, the new perspective that the view from space provides stimulates us, even forces us, to think of geology in new ways and perceive new possibilities. Truly it isn't a panacea but it is an extremely powerful tool. It has not by itself "found" an oil field or mine, but it has made significant contributions to the exploration thinking that led to the discovery of millions of barrels of oil and millions of tons of ore.

At this point, it is appropriate to consider how industry regards this new tool. Bob Porter (President, Earth Satellite Corporation) once characterized the oil and gas and mineral exploration industries' acceptance of Landsat data or any technical innovation as progressing through three stages:

1. An initial "Gee Whiz" stage;
2. An "Interesting but not yet commercial" stage; and finally
3. Full acceptance and integration of the innovation as a bona fide exploration tool.

The progression through these stages appears to be a direct function of the geologists' and geophysicists' experience and familiarity with the tool; in this instance, satellite data. Consequently, not all exploration groups progress through each stage in unison.

In the earlier "Gee Whiz" stage, the geologist may be impressed by the presence of a familiar structure or landform that is visible on the imagery, or by a subtle feature visible on an exotic digitally enhanced color image. At this stage, some are tempted to see satellite data as the answer to all exploration woes, and the potential to "oversell" its capabilities is a real danger.

This stage is usually quickly replaced by the "Interesting but not yet commercial" stage where imagery produced from the Landsat data is viewed mainly as a cheap, low resolution, aerial photo substitute. To so view Landsat imagery is to miss both the unique geologic perspective of the imagery and the potential contribution available through computer processing and data base integration of the digital data.

The final stage is characterized by the integration of the geologic information gleaned from the Landsat imagery with a complete oil and gas or minerals exploration model. At this point, the exploration geologist fully appreciates the potentials and limitations provided by the satellite system and routinely applies the satellite data to the design and execution of exploration programs. This whole process takes time. It took the gravity meter and the seismograph about 40 years to make the transit; the digital computer has progressed more rapidly.

At present, I think a healthy percentage of the exploration community is working out of the second stage of acceptance. There is a great promise that the Thematic Mapper data will provide the results necessary to convince the exploration geologist and, more importantly, the exploration financial managers, to move fully into the final stage. However, in order for this to occur, there must exist a continuity of data and, equally important, an availability of data at a reasonable (that is, user justifiable) price.

The two major advantages of Thematic Mapper data over that of the MSS system are its increased spatial resolution and its greater number of narrow, strategically placed, spectral bands (Table 1). The 30 metre pixel size will permit finer definition of ground features and thereby improve the reliability of photo-geologic interpretation of geologic structure. Of equal importance is the increased homogeneity of the types of surface material within a given pixel. The less mixed the pixel, the greater the potential of extracting useful spectral information. The increased spectral resolution is allowing geologists to map altered zones associated with mineralization based not only on iron oxides, but on the basis of recognizing rocks and soils rich in hydroxyl groups, such as many of the clays formed as a product of the mineralization process.

The increased spectral sensitivity also promises the ability to detect some types of vegetation changes that are associated with anomalous mineralization. This will be particularly helpful where soil and plants obscure the bedrock. This capability is not definitely proven, but it is theoretically possible and highly anticipated.

In addition to plate tectonics, there is a second revolution going on in the geologic thinking of petroleum exploration. The old paradigm of tightly sealed hydrocarbon traps which retain for long periods of time petroleum that was generated and migrated in the distant past is giving way to a newly evolving paradigm which envisions a much more dynamic scenario in which most, if not all, traps leak, and the generation and migration of hydrocarbons is a continuing process. This implies that there is very little, if any, really old oil or gas, rather, only new hydrocarbons generated from old rocks or retained in old traps. The hydrocarbon leaked from these imperfect traps moves vertically through the overlying rocks to the surface and, in the course of its movement, produces a host of chemical changes. The near surface environment manifests this leakage in a variety of geochemical, biological, geobotanical, or geomorphological anomalies and by the simple presence of hydrocarbon itself.

This new paradigm also has important significance to the mineral explorationists. The chemical environment created by leaking hydrocarbon has caused the emplacement of a vast amount of lead, zinc, uranium, and silver and has potentially played a role in localizing some deposits of gold, copper, and barite.

In the remainder of the talk, I would like to give you an appreciation of a few of the ways that the increased spectral and spatial resolution of the Thematic Mapper will affect geologic exploration. First, the increased spatial resolution. It is clear to us that, with careful computer and photographic processing, the quality of the TM digital data enables sharp photographic enlargements to a scale of 1:50,000 and, in some cases, larger. With clearly interpretable imagery at these scales, exploration geologists are able to significantly refine their structural interpretations compared to those made from 80 metre resolution MSS imagery.

- What was detectable only as a lineament on MSS imagery might be able to be confidently mapped as a fault.
- More importantly, some of the smaller features that indicate direction of movement along faults will be identifiable in the TM imagery, where they are lost in the lower resolution MSS imagery.

Southern Ontario (Example)

There are relatively few TM scenes available of areas with strong oil and gas interests, however, the July 25 image of Detroit does include some of the oil and gas fields of southern Ontario, Canada.

Thematic Mapper False Color Composite of Southern Ontario

On the false color image of the Ontario area, we have delineated some of the more prominent linears along with the location of the Malden, Colchester and Leamington oil and gas fields. At the Malden and Colchester fields, the hydrocarbon accumulations are in fractured, dolomitized, Ordovician limestones. The fractures trend WNW. It's a safe bet that the lineament marked on the imagery is the surface expression of a major through-going structure which is controlling the subsurface fracturing.

The Leamington field is a little younger and is located in ancient reef deposits. Reefs are known to prefer the high edge of structural blocks. The intersecting lineaments mapped on the imagery may well define two intersecting normal fault zones responsible for the uplift of a block edge and the localization of the Silurian reef.

Cement, Oklahoma (Example)

The most exciting potential contribution of the TM data is the availability of seven carefully placed spectral bands. For oil and gas exploration, these spectral bands will be extremely useful for the detection of possible surface rock alteration and geobotanical anomalies associated with microseepage of hydrocarbons from buried oil and gas accumulations. As the leaking hydrocarbons find their way to the surface, they alter the chemistry of the rocks through which they pass. At the surface, several things can occur: the altered surface chemistry may change the spectral and erosional characteristics of the surface rocks and soils and/or it may create variations in the density, type or vigor of any vegetation growing in the altered soils.

As a portion of our TM investigations, we are assessing TM's ability to identify and delineate areas of surface alteration due to microseepage of hydrocarbons at the Cement oil and gas field. The Cement field is overlain on the surface by the Rush Springs Sandstone. The Rush Springs Sandstone is a characteristic red color due to an abundance of ferric iron-oxides. The reducing chemical environment associated with the hydrocarbon microseepage appears to have altered the insoluble ferric iron to soluble ferrous iron, allowing it to be leached out of the sandstone. The result is a bleaching of the sandstone overlying the oil and gas field. We have only recently received our TM coverage of the Cement area. Our spectral analyses are therefore in their earliest stages. These next few images are pictures of our interactive image processing system and demonstrate our first cut approach at delineating the bleached area associated with the Cement field.

Cement NCC/HSV

The iron oxide rich areas are delineated on the imagery as areas of orange to red color. The quarter frame image shows the location of the red coloration following closely the outcrop of the Rush Springs Sandstone. However, the area overlying the Cement oil and gas field is one of those areas where the Rush Springs appears to have lost its strong iron oxide signature.

DEATH VALLEY, CALIFORNIA (EXAMPLE)

The first place to assess potential of TM data to map different rock types is in an area of low vegetation density and diverse rock types. Within the present range of the TM system there is clearly no more vegetation free area than Death Valley, California.

(Death Valley NCC/Death Valley FCC) - (Eigen/HSV)

The following imagery are of an approximately 1/3 TM scene area of the Death Valley, California overpass on 17 November, 1982. The scene includes a natural color, false color, eigen and HSV image.

The Hue, Saturation and Value (HSV) image is one of the more exciting images for geologic applications. Through the use of two ratios as hue and saturation, and the first eigenband as the value, the resulting HSV image possesses the spectral information of a ratio image and the spatial integrity of the first eigenband.

The hue of the image is controlled by the ratio of TM5 (1.6 microns) over TM2 (0.56 microns). The color assignments are such that high ratio values are red with decreasing values passing through the spectrum ending with the lowest values in blue. The saturation of the image is controlled by the ratio of TM5 (1.6 microns) over TM7 (2.2 microns).

TM2 was chosen for its sensitivity to ferric iron oxides; TM7 for its sensitivity to hydroxyl bands and TM5 for its high variance and broad information content. The 5/2 ratio will have high value (red hue) over areas of high ferric iron content, vegetation, as well as an assortment of other surface materials. The 5/7 ratio will have particularly high values (high saturation on the output image) over areas which contain hydroxyl bearing minerals or surface materials containing free water (e.g., clays, hydrated salts and vegetation). The first eigenband represents a positively weighted sum of the seven TM bands and thus provides excellent geomorphologic information allowing for precise geographic locations of the image's spectral information.

We suggest comparison of this image with the 1:250,000 scale Death Valley sheet of the Geologic Map series of California. Through comparison with the geologic map, some interesting examples of the unique information content of the HSV image appear along the northeastern flank of the Panamint Mountains, the eastern Funeral Mountains and the northern portions of the Resting Spring

Mountains. The lower Paleozoic marine section along the northeastern flank of the Panamints is clearly distinguished from the older (PC?) section to the west. The small outcrops of Tertiary volcanics overlying the Paleozoic section are also clearly distinguishable. Note, however, that the Paleozoic marine section to the north (Tucki Mountain area) is spectrally "confused" with the Tertiary volcanics. The Tucki section is distinctly different from the Paleozoic sediments to the south of Black Water Wash, however, it is not immediately clear why its 5/2 ratio should be so spectrally similar to that of the Tertiary volcanics. Along the eastern portions of the Funeral Mountains and the Resting Spring Range, there are several examples of stratigraphic horizons which are clearly mappable on the HSV imagery and have been grouped into the Cambrian marine unit on the 1:250,000 scale geologic map. Although such groupings are obviously necessary during geologic mapping, the ability to map the individual lithologic beds on the HSV imagery significantly augments the information available on the geologic maps.

SUMMARY

We in the exploration industry find ourselves in a very challenging situation. World consumption of energy and mineral commodities is ever increasing, while at the same time, we are at a point where most of the large easy-to-discover, cheap-to-produce petroleum accumulations and mineral deposits have been located and many of these already exploited and depleted.

However, on the bright side, our technology is continuing to develop new tools with which geologic explorationists can evolve and test new geologic concepts. These new concepts allow the geologist to view exploration challenges with a new set of glasses, leading to such discoveries as finding oil in fractured volcanic rocks in the Great Basin of Nevada and to the thought of drilling through igneous and metamorphic rocks to find underlying oil in the Appalachian Mountains.

The improvements of Thematic Mapper data over multispectral scanner data brings us to the point that we are able to exploit satellite imagery at about the same scale that we have used aircraft data in the past. Certainly, improved spatial and spectral resolution and wider spectral coverage would be welcomed and stereoscopic imagery will be a great boon. However, it appears to us that the present TM system offers a near optimum balance between resolution requirements and data handling capabilities.

In summary, we feel confident that specially enhanced Thematic Mapper imagery will make a very significant contribution to the oil and gas and mineral exploration industries. The TM's increased spatial resolution will enable the production of larger scale imagery, which will greatly increase the amount of geomorphic and structural information interpretable. TM's greater spectral resolution, combined with the smaller, more homogeneous pixels, should enable a far greater confidence in mapping lithologies and detecting geobotanical anomalies from space. The results from its applications to hydrocarbon and mineral exploration promise to bring the majority of the geologic exploration community into that final stage of acceptance and routine application of the satellite data.

Table 1

COMPARISON OF LANDSAT -1, -2, -3 AND -4 MULTISPECTRAL
SCANNER CHARACTERISTICS WITH THOSE OF LANDSAT-4 THEMATIC MAPPER

	MSS	TM
Resolution:	∿ 80m	∿ 30m
Wavelength Bands:		
	4 = 500 - 600nm	1 = 450 - 520nm
	5 = 600 - 700nm	2 = 520 - 600nm
	6 = 700 - 800nm	3 = 630 - 690nm
	7 = 800 - 1100nm	4 = 760 - 900nm
		5 = 1550 - 1750nm
		6 = 10400 - 12500nm
		7 = 2080 - 2080nm

IMPLICATIONS OF INFORMATION FROM LANDSAT-4 FOR PRIVATE INDUSTRY

By Dr. John R. Everett and Dr. Jon D. Dykstra
Earth Satellite Corporation
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The broader spectral coverage and higher resolution of Landsat-4 Thematic Mapper (TM) data open the door for identification from space of spectral phenomena associated with mineralization and microseepage of hydrocarbon. Digitally enhanced image products generated from TM data allow the mapping of many major and minor structural features that mark or influence emplacement of mineralization and accumulation of hydrocarbons. These improvements in capabilities over multispectral scanner data will accelerate the acceptance and integration of satellite data as a routinely used exploration tool that allows rapid examination of large areas in considerable detail.

There is a fortuitous synchronous development of satellite remote sensing, and the concepts of plate tectonics and vertical migration of hydrocarbons - two paradigms which are reshaping geological exploration thinking. The steadily improving quality of satellite data is providing geologists with a valuable tool with which to test, revise and exploit these new concepts.

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Since the early 1960's, the science of geology has been undergoing a major revolution. The new paradigm of plate tectonics and seafloor spreading is replacing the older paradigm of a rigid, stable earth. Inherent in the acceptance of plate tectonic theory is a growing appreciation of the role of plate motion in determining the location of mineral deposits and hydrocarbon accumulations. It is fortunate that developments in spaceborne remote sensing have paralleled these developments in geologic thinking. As a consequence, we have remote sensing tools that view the earth with appropriate scale and scope to enable us to appreciate and map the regional structures that reflect the motions of continent-sized segments of the earth's crust. We received our first glimpses of the earth from space with photos from the Apollo and Gemini flights. The first three Landsat satellites gave us near ubiquitous high resolution (80 metre) coverage in four spectral bands. These data have had and continue to have enormous impact on all facets of perception and management of renewable and non-renewable natural resources and the environment.

Before speculating on the impact of the new data types from Landsat-4, it is useful to take a look at the role data from the first three Landsat satellites have in geologic exploration and their current level of acceptance. In a general sense, Landsat data has made its major contribution to hydrocarbon exploration in the spatial domain. In mineral exploration, Landsat has revealed some spectral information, but again the major contribution is spatial. The synoptic view of over 34,000 square kilometres of the earth's surface on a single Landsat image permits the detection and mapping of major regional structures associated with the geologic development of entire geologic provinces. It is also possible, through special digital enhancements, to map some of the more subtle surface expressions of fracturing, folding and alteration associated with buried hydrocarbon accumulations and the emplacement of mineral deposits. The data make it possible to interrelate widely separated geologic features and detect subtle changes that occur over tens of miles and, hence, have gone unnoticed on conventional types of data. Perhaps most important of all, the new perspective that the view from space provides stimulates us, or forces us, to think of geology in new ways and perceive new possibilities. Truly it isn't a panacea but it is an extremely powerful tool. It has not by itself "found" an oil field or mine, but it has made significant contributions to the exploration thinking that led to the discovery of millions of barrels of oil and millions of tons of ore.

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At present, I think a healthy percentage of the exploration community is working out of the second stage of acceptance. There is a great promise that the Thematic Mapper data will provide the results necessary to convince the exploration geologist and, more importantly, the exploration financial managers, to move fully into the final stage. However, in order for this to occur, there must exist a continuity of data and, equally important, an availability of data at a reasonable (that is, user justifiable) price.

The two major advantages of the Thematic Mapper data on Landsat-4 over the MSS system are its increased spatial resolution and its greater number of narrow, strategically placed, spectral bands (Table 1). These new data are so spectacular, they will undoubtedly stimulate a new round of the "Gee Whiz" phase. The increased spectral resolution is allowing us to map altered zones associated with mineralization based not only on iron oxide but on the basis of recognizing rocks and soils rich in hydroxyl groups, such as many of the clays formed as a product of hydrothermal alteration. The increased spectral range and resolution promise the ability to detect some types of vegetation changes that are associated with anomalous mineralization. This will be particularly helpful where soil and plants obscure the bedrock. This capability is not definitely proven, but theoretically possible and highly anticipated.

There is a second revolution going on in petroleum exploration geologic thinking in addition to the plate tectonic revolution. The old paradigm calls for tightly sealed hydrocarbon traps retaining for long periods of time (tens or hundreds of millions of years) petroleum that was generated and migrated in the distant past. The newly evolving paradigm envisions a much more dynamic scenario in which most, if not all, traps leak, and the generation and migration of hydrocarbons is a continuing process. This implies that there is very little, if any, really old oil or gas, rather, only new hydrocarbons generated from old rocks or retained in old traps. The hydrocarbon leaked from these imperfect traps moves vertically through the overlying rocks to the surface and, in the course of its movement, produces a host of chemical changes. The near surface environment manifests this leakage in a variety of geochemical, biological, geobotanical, or geomorphological anomalies or the simple presence of hydrocarbon itself.

Mineral exploration is not immune to the consequences of this paradigm. This peripatetic hydrocarbon has caused the emplacement of a vast amount of lead, zinc, uranium, and silver and has potentially played a role in localizing some deposits of gold, copper, and barite. This means that both petroleum and mineral geologists will need to be cognizant of the depositional and thermal histories of areas.

In the remainder of the talk, I would like to give you an appreciation of a few of the ways that the increased spectral and spatial resolution of the Thematic Mapper will affect geologic exploration. First, the increased spatial resolution. It is clear to us that, with careful computer and photographic processing, the quality of the TM digital data enables sharp photographic enlargements to a scale of 1:50,000 and, in some cases, larger. With clearly interpretable imagery at these scales, exploration geologists are able to significantly refine their structural interpretations compared to those made from 80 metre resolution MSS imagery.

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The iron oxide rich areas are delineated on the imagery as areas of orange to red color. The quarter frame image shows the location of the red coloration following closely the outcrop of the Rush Springs Sandstone. However, the area overlying the Cement oil and gas field is one of those areas where the Rush Springs appears to have lost its strong iron oxide signature.

DEATH VALLEY, CALIFORNIA (EXAMPLE)

The first place to assess potential of TM data to map different rock types is in an area of low vegetation density and diverse rock types. Within the present range of the TM system there is clearly no more vegetation free area than Death Valley, California.

(Death Valley NCC/Death Valley FCC) - (Eigen/HSV)

The following imagery are of an approximately 1/3 TM scene area of the Death Valley, California overpass on 17 November, 1982. The scene includes a natural color, false color, eigen and HSV image.

The Hue, Saturation and Value (HSV) image is one of the more exciting images for geologic applications. Through the use of two ratios as hue and saturation, and the first eigenband as the value, the resulting HSV image possesses the spectral information of a ratio image and the spatial integrity of the first eigenband.

The hue of the image is controlled by the ratio of TM5 (1.6 microns) over TM2 (0.56 microns). The color assignments are such that high ratio values are red with decreasing values passing through the spectrum ending with the lowest values in blue. The saturation of the image is controlled by the ratio of TM5 (1.6 microns) over TM7 (2.2 microns).

TM2 was chosen for its sensitivity to ferric iron oxides; TM7 for its sensitivity to hydroxyl bands and TM5 for its high variance and broad information content. The 5/2 ratio will have high value (red hue) over areas of high ferric iron content, vegetation, as well as an assortment of other surface materials. The 5/7 ratio will have particularly high values (high saturation on the output image) over areas which contain hydroxyl bearing minerals or surface materials containing free water (e.g., clays, hydrated salts and vegetation). The first eigenband represents a positively weighted sum of the seven TM bands and thus provides excellent geomorphologic information allowing for precise geographic locations of the image's spectral information.

We suggest comparison of this image with the 1:250,000 scale Death Valley sheet of the Geologic Map series of California. Through comparison with the geologic map, some interesting examples of the unique information content of the HSV image appear along the northeastern flank of the Panamint Mountains, the eastern Funeral Mountains and the northern portions of the Resting Spring Mountains. The lower Paleozoic marine section along the northeastern flank of the Panamints is clearly distinguished from the older (PC?) section to the west. The small outcrops of Tertiary volcanics overlying the Paleozoic section are also clearly distinguishable. Note, however, that the Paleozoic marine section to the north (Tucki Mountain area) is spectrally "confused" with the Tertiary volcanics. The Tucki section is distinctly different from the Paleozoic sediments to the south of Black Water Wash, however, it is not immediately clear why its 5/2 ratio should be so spectrally similar to that of the Tertiary volcanics. Along the eastern portions of the Funeral Mountains and the Resting Spring Range, there are several examples of stratigraphic horizons which are clearly mappable on the HSV imagery and have been grouped into the Cambrian marine unit on the 1:250,000 scale geologic map. Although such groupings are obviously necessary during geologic mapping, the ability to map the individual lithologic beds on the HSV imagery significantly augments the information available on the geologic maps.

SUMMARY

We in the exploration industry find ourselves in a very challenging situation. World consumption of energy and mineral commodities is ever increasing, while at the same time, we are at a point where most of the large easy-to-discover, cheap-to-produce petroleum accumulations and mineral deposits have been located and many of these already exploited and depleted.

However, on the bright side, our technology is continuing to develop new tools with which geologic explorationists can evolve and test new geologic concepts. These new concepts allow the geologist to view exploration challenges with a new set of glasses, leading to such discoveries as finding oil in fractured volcanic rocks in the Great Basin of Nevada and to the thought of drilling through igneous and metamorphic rocks to find underlying oil in the Appalachian Mountains.

The improvements of Thematic Mapper data over multispectral scanner data brings us to the point that we are able to exploit satellite imagery at about the same scale that we have used aircraft data in the past. Certainly, improved spatial and spectral resolution and wider spectral coverage would be welcomed and stereoscopic imagery will be a great boon. However, it appears to us that the present TM system offers a near optimum balance between resolution requirements and data handling capabilities.

In summary, we feel confident that specially enhanced Thematic Mapper imagery will make a very significant contribution to the oil and gas and mineral exploration communities. The TM's increased spatial resolution will enable the production of larger scale imagery, which will greatly increase the amount of geomorphic and structural information interpretable. TM's greater spectral resolution, combined with the smaller, more homogeneous pixels, should enable a far greater confidence in mapping lithologies and detecting geobotanical anomalies from space. The results from its applications to hydrocarbon and mineral exploration promise to bring the majority of the geologic exploration community into that final stage of acceptance and routine application of the satellite data.

Table 1
COMPARISON OF LANDSAT -1, -2, -3 and -4 MULTISPECTRAL
SCANNER CHARACTERISTICS WITH THOSE OF LANDSAT-4 THEMATIC MAPPER

	MSS	TM
Resolution:	∿80m	∿30m
Wavelength bands:		
	4 = 500 - 600nm	1 = 450 - 520nm
	5 = 600 - 700nm	2 = 520 - 600nm
	6 = 700 - 800nm	3 = 630 - 690nm
	7 = 800 -1100nm	4 = 760 - 900 nm
		5 = 1550 - 1750 nm
		6 = 10,400 - 12,500nm
		7 = 2080 - 2350nm

SELECTING BAND COMBINATIONS WITH THEMATIC MAPPER DATA.

by

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Background. Since the human eye employs three primary colors, and the Thematic Mapper returns seven bands of data, one obvious problem that arises in making color composite images is the choice of bands. The choice in non-trivial, since three bands can be selected from seven in 35 ways. Also, any band can be assigned any color. This gives a total of 210 different possible color presentations of TM three-band images. In this note we present a way of reducing that 210 to a single choice, decided uniquely by the statistics of a scene or subscene, and taking full account of any correlations that exist between different bands.

We should remark here that one well-known and widely used approach to this problem of choice is through the use of principal component images. However, such methods offer a new problem as great as the one that they solve. For although the first three principal components contain in a statistical sense as much information as can be presented using three colors, the resulting scene is completely data dependent. It is thus difficult for an interpreter to apply any previous experience of color-surface relationships to the analysis of a principal components image.

Definition of the method. Consider the 7 x 7 variance-covariance matrix M for the scene or subscene, ignoring for the moment the fact that the thermal band is of inherently lower resolution than the rest. Any triplet of bands will be represented within this 7 x 7 matrix by a 3 x 3 submatrix.

Considering now the 3-dimensional subspace spanned by any particular band triplet, the associated variance-covariance matrix defines an ellipsoid within the subspace. Further, the sum of the squared principal axes of this ellipsoid represents the total variance accounted for by these three bands (see Figure 1). One could plausibly (but as we shall see, wrongly) argue that the best three bands are those with the largest sum of squared principal axes, and hence accounting for the largest total variance. This is, after all, exactly the argument applied in employing principal component images. Since the trace of a matrix is invariant under rotational transformations, and since the sum of squared principal axes is equal to that trace, the band triplet that accounts for the most possible variance can be found from the original variance-covariance matrix simply by selecting the three bands with the largest diagonal elements. There is no need to examine all 35 band combinations.

To see what is wrong with this approach, consider an extreme case where there happens to be perfect correlation between a pair of bands. For convenience, suppose that those bands are 1 and 2, and suppose that the variance of band 1 (and therefore of 2) is larger than that of any other band. The 7 x 7 matrix M then has the form:

$$\left(\begin{array}{cc|ccccc} a & a & \cdots & & & & \\ a & a & \cdots & & & & \\ \hline \vdots & \vdots & b & & & & \\ & & & c & & & \\ & & & & \ddots & & \\ & & & & & \ddots & \\ \vdots & \vdots & & & & & \ddots \end{array}\right)$$

where a>b,c,...

The rotation matrix that will diagonalize the upper left 2 x 2 submatrix then has the form:

$$\begin{pmatrix} 1/\sqrt{2} & \frac{1}{\sqrt{2}} & \vdots & \\ -1/\sqrt{2} & 1/\sqrt{2} & \vdots & 0 \\ & & \vdots & \\ & 0 & \vdots & I \end{pmatrix}$$

and thus after rotation the upper left 2 x 2 submatrix will have the form:

$$\begin{pmatrix} 2a & 0 \\ 0 & 0 \end{pmatrix}$$

As expected, one eigenvalue is zero; but the other is the sum of the variances from the original bands 1 and 2. Since a is assumed to be large, both bands 1 and 2 will be included in the triplet that accounts for maximum variance -- despite the fact that if either one of them is used, adding the other contributes no new information.

The problem lies in the use of total variance as the measure for the information content of the band triplets. This is equivalent to use of the sum of squares of ellipsoid principal axes, and there is no penalty associated with a very small principal axis provided that it occurs in association with a large axis (see Figures 2 and 3), as was the case for the above example.

We propose the use of a new measure for the information content of the triplet, and one that avoids the undesirable property demonstrated above. We will select the ellipsoid of maximum volume. This discourages selection of pairs of bands with high correlation, since in such cases one eigenvalue will be close to zero and the corresponding ellipsoid volume will be small.

Since the ellipsoid volume is simply $4/3\pi abc$, where a, b, and c are the principal axes of the ellipsoid, the volume of the ellipsoid associated with a particular band triplet is a constant multiple of the square root of the product of the eigenvalues for the 3 x 3 variance-covariance matrix of that triplet. However, under rotational transformation the product of the eigenvalues is equal to the determinant of the original 3 x 3 submatrix. Thus we can select the band triplet that provides the ellipsoid of maximum volume simply by computing and ranking in order the determinants of each 3 x 3 principal submatrix of the original matrix M. The band triplets associated with these determinants will then be ranked in order of decreasing overall information content. Given the original matrix M, the total computation to achieve this ranking is trivial. It requires a few hundred multiplications, followed by a sort of a list of 35 items. A BASIC program to perform this is given as an Appendix to this note.

This procedure gives the best triplet, but the assigment of colors is still to be made. Now we can make use of the actual variances (the diagonal elements of M). Since the eye is most sensitive to green, next to red, and least to blue, we will assign green to the band triplet member of maximum variance (i.e. most variation within the image), red to the triplet member of second largest variance, and blue to the triplet member of smallest variance. The definition of bands for production of a color image is now complete.

Examples and comments. The procedure has been applied to a number of scenes of very different ground cover, including Washington D.C., Death Valley, and Cement, Oklahoma. The results for Washington and for Death Valley are given in Tables 1 and 2, together with the associated variance-covariance matrices. The following comments apply to all scenes studied to date.

1) The band combination 1,4,5 (in the order blue, red, green) is usually, but not always, the selected triplet. In cases where it does not rank first,

it ranks second or third.

2) The natural color combination 1,2,3 and the standard false color combination 2,3,4, both place far down in the rankings. In the case of Washington, the natural color combination is 29th (lower than anything except some thermal band combinations, which are low for another reason to be discussed shortly); the 2,3,4 combination was ranked in 16th place. For Death Valley, the 1,2,3 natural color combination ranked 32nd, and the 2,3,4 combination just above it, at 31st. This is presumably a consequence of the very high correlations between the first four bands.

3) Triplets that rank high always include either band 5 or band 6 (note: the bands here are ordered by increasing wavelength, so the thermal band is band 7). This emphasizes the great importance of these new bands on general information-bearing grounds.

4) The triplet selected is not always or even usually the triplet with the greatest individual variances, though large variances are naturally preferred somewhat in the selection process.

Other considerations and comments.

1) The statistical analysis performed here used P tapes (all that we had available) in which the original histograms had already been modified by the gains and offsets. It would be preferable to work with data that have had no gains or offsets applied, i.e., with A tapes prior to any radiometric correction. If band selection of this type becomes common, it would be nice to have A tapes generally available from the EROS Data Center.

2) The thermal band is of lower resolution than the rest, thus it would not be appropriate to give it the same weight in the selection process. How should one therefore de-weight it? One argument runs as follows: The maximum information that a scene can contain is given by the number of pixels, since

In the ultimate case there would be no correlation between pixels, and each would carry independent information about some feature of the surface. In such a case, the amount of information that the thermal band can contribute is only 1/16th that of the other bands, because there are 16 times fewer pixels in that band. Therefore one should deweight the thermal channel by a factor of 16. Such deweighting was performed in the experiments reported here. However, we should also note that this made no difference at all to the preferred band triplets, since even without deweighting we found no case where a triplet involving the thermal channel was in the top five.

3) It is obvious when one looks at images created from the triplet 1,4,5 that for some applications this combination will be much inferior to others, such as natural color and standard false color. This restates the old truth, one man's noise is another man's signal. However, the preferred triplets have another advantage: they provide images of unusual clarity, with far less residual striping than is seen in, for example, the natural color images.

4) Although combinations such as 1,4,5 produce images that are at first sight unfamiliar and unusual, the assigned colors are not scene-dependent. Thus in contrast to the scene dependent colors of principal component or ratio images, the interpreter quickly learns to associate colors with particular ground condition. We therefore believe that there are definite advantages to seeking color composites from the original bands, rather than through band ratios or band combinations.

Figure 1: The variance-covariance ellipsoid, principal axes $\sqrt{\lambda_1}$, $\sqrt{\lambda_2}$, $\sqrt{\lambda_3}$.

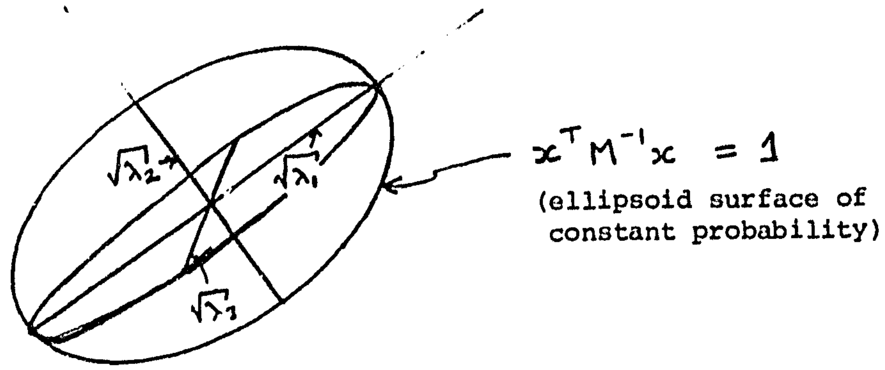
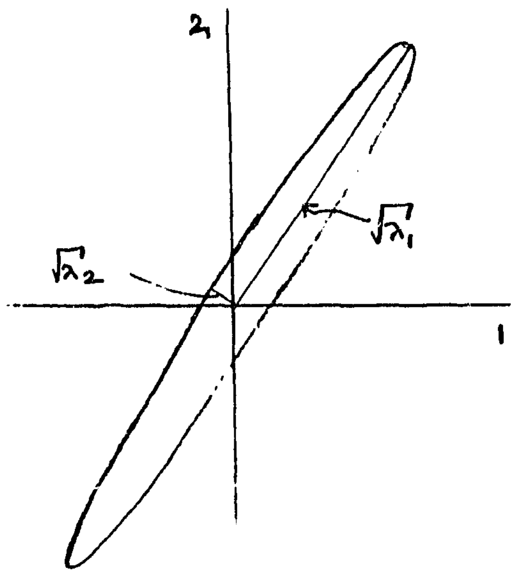


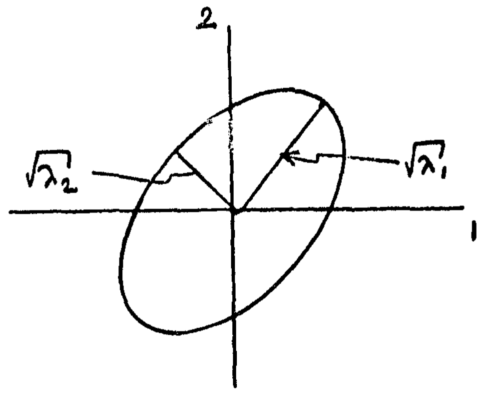
Figure 2. High correlation, bands 1 and 2.



$\lambda_1 + \lambda_2$ large,

$\lambda_1 . \lambda_2$ small

Figure 3. Low correlation, bands 1 and 2, but lower individual variances.



$\lambda_1 + \lambda_2$ smaller than in Fig.2.

$\lambda_1 . \lambda_2$ larger than in Fig. 2.

Based on ellipsoid volumes, Fig. 2 case is preferred over Fig. 1 case, although the former accounts for a greater total variance.

APPENDIX: THE BEST-BAND PROGRAM.

```
20   PRINT "SELECTION OF BEST THREE BANDS BASED ON ELLIPSOID VOLUME"
30   PRINT "DEATH VALLEY WITH REDUCED THERMAL VARIANCE"
40   DIM R(36),Q(36)
50   DIM U(36),V(36)
60   DIM M(8,8)

70 REMARK: M is the variance-covariance matrix for the scene or subscene.
80 REMARK: The arrays R,Q,U and V are storage arrays used in the program.
90 REMARK: Note that the program assumes that band 7 is the thermal data,
and band 6 is the 2.2 micrometre data.
100 REMARK: The instructions 190 to 230 (except for 220, which sets a count)
reduce the variance of the thermal channel to allow for the lower spatial
resolution of the thermal channel pixel.

190  FOR I = 1 TO 6
200 M(I,7) = M(I,7) / 4
210  NEXT
220 C = 1
230 M(7,7) = M(7,7) / 16
240  PRINT "RANK        DETERMINANT     COMBINATION"
250  FOR I = 1 TO 5
260  FOR J = I + 1 TO 6
270  FOR K = J + 1 TO 7
280 D1 = M(I,I) * (M(J,J) * M(K,K) - M(J,K) ^ 2)
290 D2 = M(I,J) * (M(J,K) * M(I,K) - M(I,J) * M(K,K))
300 D3 = M(I,K) * (M(I,J) * M(J,K) - M(I,K) * M(J,J))
310 DT = D1 + D2 + D3

315 REMARK: The next instruction makes the determinant an integer; this is
not necessary, it is done for convenience of output only.

320 DT =  INT (DT)
330 N = 100 * I + 10 * J + K
340 R(C) = DT:Q(C) = N
350 C = C + 1
360  NEXT
370  NEXT
380  NEXT

385 REMARK: The next piece of code sorts the determinant into descending order.

390  FOR I = 1 TO 35
400 N = 0
410  FOR J = 1 TO 35
420  IF R(I) | R(J) THEN 440
430 N = N + 1
440  NEXT
450 U(N) = R(I):V(N) = Q(I)
460  NEXT
470  FOR I = 1 TO 35
480  PRINT I,U(I),V(I)
490  NEXT
500  PR# 0
510  END
```

SELECTION OF BEST THREE BANDS BASED ON ELLIPSOID VOLUME
WASHINGTON SCENE WITH REDUCED VARIANCE ON THE THERMAL CHANNEL

VARIANCE-COVARIANCE MATRIX, THERMAL BAND IS BAND 7

53.32	27.41	35.74	5.86	36.04	33.56	7.77
27.41	17.01	21.35	11.36	29.35	21.29	4.13
35.74	21.35	31.66	20.01	46.56	31.03	6.69
5.86	11.36	20.01	131.71	131.64	38.14	8.26
36.04	29.35	46.56	131.64	210.83	86.25	19.1
33.56	21.29	31.03	38.14	86.25	50.01	11.51
7.77	4.13	6.69	8.26	19.1	11.51	9.8

}

Table 1.a Variance-covariance matrix for the Washington D.C. scene.

SELECTION OF BEST THREE BANDS BASED ON ELLIPSOID VOLUME
THIS IS THE WASHINGTON SCENE WITH REDUCED VARIANCE ON THE THERMAL CHANNEL

RANK	DETERMINANT	COMBINATION
1	433858	145
2	205811	345
3	138551	146
4	124784	245
5	101638	456
6	71723	156
7	62960	346
8	49759	135
9	39992	134
10	39609	246
11	36060	356
12	22847	125
13	21953	256
14	16732	124
15	11646	235
16	9709	234
17	7967	136
18	5094	457
19	4752	157
20	3634	126
21	3606	147
22	2294	467
23	2194	357
24	1945	347
25	1616	236
26	1386	567
27	1348	257
28	1130	247
29	727	123
30	688	167
31	276	367
32	215	137
33	175	267
34	84	127
35	43	237

TABLE 1.b Ranked results for Washington D.C. scene.

SELECTION OF BEST THREE BANDS BASED ON ELLIPSOID VOLUME
DEATH VALLEY WITH REDUCED THERMAL VARIANCE

VARIANCE-COVARIANCE MATRIX, THERMAL BAND IS BAND 7

251.64	146.31	198.55	176.41	246.36	144.63	5.3
146.31	90.4	125.4	112.95	178.63	105.16	10.33
198.55	125.4	181.12	163.27	276.44	162.93	22.5
176.41	112.95	163.27	159.7	262.74	152.99	14.79
246.36	178.63	276.44	262.74	627.47	366.9	75.38
144.63	105.16	162.93	152.99	366.9	223.38	48.73
5.3	10.33	22.5	14.79	75.38	48.73	69.89

}

Table 2.a <u>Variance-covariance matrix for the Death Valley scene.</u>

SELECTION OF BEST THREE BANDS BASED ON ELLIPSOID VOLUME
DEATH VALLEY WITH REDUCED THERMAL VARIANCE

RANK	DETERMINANT	COMBINATION
1	1462581	145
2	859695	156
3	684248	135
4	601687	146
5	432952	345
6	346425	157
7	328331	356
8	319827	245
9	275534	456
10	263989	136
11	219239	256
12	204146	125
13	167450	346
14	137060	357
15	127643	246
16	121117	167
17	107494	457
18	103781	235
19	89506	257
20	76827	126
21	75913	134
22	49163	367
23	40621	467
24	39230	236
25	37614	147
26	31621	267
27	21579	137
28	21322	124
29	20256	567
30	9168	347
31	8118	234
32	7895	123
33	7197	247
34	5037	127
35	2407	237

Table 2.b Ranked results for Death Valley scene.